SEARCHING FOR ELECTROMAGNETIC COUNTERPARTS OF GRAVITATIONAL WAVE TRANSIENTS

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A pioneering electromagnetic (EM) observation follow-up program of candidate gravitational wave (GW) triggers has been performed, Dec 17 2009 to Jan 8 2010 and Sep 4 to Oct 20 2010, during the recent LIGO/Virgo run. The follow-up program involved ground-based and space EM facilities observing the sky at optical, X-ray and radio wavelengths. The joint GW/EM observation study requires the development of specific image analysis procedures able to discriminate the possible EM counterpart of GW trigger from background events. The paper shows an overview of the EM follow-up program and the developing image analysis procedures as they are applied to data collected with TAROT and Zadko.

1 Introduction

The LIGO ¹ and Virgo ² detectors aim at the first direct detection of gravitational waves from very energetic astrophysical events. The most promising sources are mergers of neutron stars (NS) and/or stellar mass black holes (BH) and the core collapse of massive stars. More exotic sources include cosmic string cusps. It is likely that a fraction of the large energy reservoir associated to those sources be converted into electromagnetic radiation. This possibility is a feature of several astrophysical scenarios. For instance, Gamma-Ray Bursts (GRBs) are thought to be associated with the coalescence of NS-NS or NS-BH binaries or the collapse of very massive stars (see ³ and references therein). Another scenario associated with compact object mergers is the prediction ⁴ of an isotropic EM emission from supernova-like transients powered by the radioactive decay of heavy elements produced in merger ejecta (this is referred to as the *kilonova* model). There are models that predict that cusps produce electromagnetic radiation ⁵.

In this respect, multi-messenger GW and EM astronomy is a very promising field of research. An electromagnetic counterpart discovered through a follow-up of a gravitational wave candidate event would considerably increase the confidence in the astrophysical origin of the event. The detection of an EM counterpart would give the precise localization and possibly lead to the identification of the host galaxy and redshift. Furthermore, EM and GW observations

provide complementary insights into the progenitor and environment physics. In the long term combined measurements of the luminosity distance through GW radiation and redshifts through EM observations may allow a new way of estimating some cosmological parameters.

2 Enabling EM Follow-up of Candidate GW Events

2.1 Selection of Candidate GW Events

A first program of EM follow-up to GW candidates took place (Dec 17 2009 to Jan 8 2010 and Sep 4 to Oct 20 2010) during the last LIGO/Virgo observation periods, thanks to the development of a low-latency GW data analysis pipeline that uses real time gravitational wave triggers to obtain prompt EM observations to search for the EM counterparts.

One of the challenges of successfully obtaining "target of opportunity" EM observations is to identify the GW candidates quickly: the data from the three operating detectors (the two LIGOs and Virgo) must be transferred and analyzed in near-real time. As soon as the data become available, three search algorithms (Omega Pipeline, coherent Wave Burst both described in ^{6,7} and Multi Band Template Analysis ⁸) run over the data. For each generated trigger, the direction of arrival of the wave (and hence potential sky position of the source) is estimated using a method based on differences in arrival time at each detector. The event candidates are collected in the Gravitational-wave candidate event database (GraCEDb). Two software packages LUMIN and GEM select statistically significant triggers and determine the telescope pointing positions. This process typically takes ~ 10 minutes. It is followed by a manual event validation. A team of trained experts is on duty and their role is to rapidly coordinate with scientists at the GW detectors to evaluate the detector performances. If no problem is found the alert is sent to telescopes. The entire process is typically completed within 30 minutes. The triggers selected as GW candidates for EM follow-up are the ones detected in triple coincidences and with a power above a threshold estimated from the distribution of background events. A full description of the GW trigger selection and the entire EM follow-up process is detailed in ⁹.

2.2 Sky Pointing strategy

The uncertainty in the source direction reconstruction scales inversely with the signal-to-noise ratio ¹⁰. GW events near the detection threshold are localized into regions of tens of square degrees. Generally, the error regions have a non-trivial geometrical shape, often formed of several disconnected patches. Follow-up EM-telescopes with a wide Field Of View (FOV) are thus required. However, the majority of those telescopes have a FOV which is much smaller than the GW angular error box. Additional priors are necessary to improve the location accuracy and increase the chance that the actual source be in the selected FOV. The observable Universe is limited to an horizon of 50 Mpc, taking into account the detector sensitivity to the signals coming from NS binaries ¹¹. The observation of the whole GW error box is not required ¹², but it can be restricted to the regions occupied by Globular Clusters and Galaxies within 50 Mpc, listed in the Gravitational Wave Galaxy Catalog ¹³. Tens of thousands of galaxies are included within this horizon and the GW observable sources are more likely to be extragalactic.

To determine the telescope pointing position, the probability sky map based on GW data is "weighted" taking into account the mass and the distance of nearby galaxies ¹⁴ and globular clusters. It is assumed that the probability of a given galaxy being the host of the actual source i) is directly proportional to the galaxy's mass (the blue luminosity is used as proxy for the mass and thus for the number of stars) and, ii) is inversely proportional to the distance.

The follow-up program involved ground-based and space EM facilities: the *Liverpool Telescope*, the *Palomar Transient Factory* (PTF), *Pi of the Sky*, *QUEST*, *ROTSE III*, *SkyMapper*, *TAROT* and the *Zadko Telescope* observing the sky in the optical band, the *Swift* satellite with X-ray and UV/Optical telescopes and the radio interferometer *LOFAR*. The observing strategy employed by each telescope will be described in ⁹.

The cadence of EM observations is guided by the expected EM counterpart. The optical afterglow of an on-axis GRB peaks few minutes after the EM/GW prompt emission. The kilonova model predicts an optical light curve that peaks a day after the GW event, due to the time that the out flowing material takes to become optically thin. The agreement with the EM facilities allowed observations as soon as possible, the day after the GW event and, repeated observations over longer time-lag to follow the transient light curve dimming.

During the recent winter and summer LIGO/Virgo runs a total of 14 alerts have been sent out to the telescopes and 9 of them led to images being taken.

3 Optical Transient Search in the Wide-Field Telescope Observations

Once the follow-up observations are completed, the collected set of images needs to be analyzed to decide the presence or not of an optical transient of interest. The analysis method is conceptually similar to one used to study a GRB afterglow with a main difference: the arc minute localization of the current generation gamma-ray observatories allows a significant reduction of the search area with respect to the GW observations.

Searching for optical transients in a large sky area requires the development and use of specific image analysis procedures able to discriminate the EM counterpart from background/contaminant events. Several analysis pipelines are being developed and tested by groups within the LIGO Scientific Collaboration and the Virgo Collaboration in partnership with astronomers.

This section describes one of the considered approaches based on the cross-correlation of object catalogs obtained from each image. The resulting pipeline has been designed and tested with the images collected by the two TAROT and the Zadko telescopes.

 $TAROT^{15}$ are two robotic 25 cm telescopes with a FOV of 3.5 square degrees located in Calern (France) and in La Silla (Chile). In case of a GW alert, TAROT followed a nominal observation schedule including six consecutive images with 180 second exposures during the first night and same for the three following nights. An exposure of 180 seconds corresponds to a red limiting magnitude of 17.5 under ideal conditions. $Zadko^{16}$ is a 1 meter telescope with a FOV of 0.17 square degrees located in Gingin (Western Australia). For each GW trigger, Zadko followed a nominal observation schedule including a mosaic of five fields with six consecutive images during the first night and same for the three following nights. A 120 sec exposure corresponds to a red limiting magnitude of 20.5 under ideal conditions.

The main steps of the fully automated analysis pipeline are as follows:

- 1) extraction of the catalog of objects visible in the images using SExtractor ¹⁷;
- 2) removal of "known objects" listed in USNO-A2.0 or USNO-B star catalogs that are complete down to a fainter magnitude than the collected images by using a positional cross-correlation tool match ¹⁸:
- 3) trace objects in common to several image catalogs by using a cross-positional check. This results in a light curve for each traced object;
- 4) rejection of "rapid contaminating transients" (like cosmic rays, asteroids or noise): the presence is required in at least four consecutive images;
- 5) rejection of "background transients": the objects are selected in the image regions associated with the galaxies within 50 Mpc. A circular region with a diameter equal to 4 times the major

axis galaxy size is used. This is to take into account the possible offset between the host galaxy center and the optical transients (observed up to tens of kpc for GRBs);

6) rejection of "contaminating events" like galaxies, variable stars or false transients by analyzing the light curves. The code selects the objects that show a luminosity dimming with time. Assuming that the dimming is described by a single power-law $\mathcal{L} \propto t^{-\beta}$, corresponding to a linear variation in terms of magnitude equal to $m = 2.5\beta \log_{10}(t) + C$, a "slope index" 2.5β is defined and evaluated for each objects. The expected "slope index" for GRB afterglows and kilonova-like light curves is around 2.5-3. In practice, a conservative cut is applied by selecting as the possible EM counterparts the objects with the "slope index" larger than 0.5. This value has been checked using Monte Carlo simulations.

The preliminary results on the pipeline sensitivity indicate for a survey red limiting magnitude of 15.5 that the majority of GRB afterglows can be detected further away the GW horizon distance of 50 Mpc, while the kilonova objects can be detected up to a distance of 15 Mpc. These results are obtained by repeatedly running the pipeline over sets of TAROT and Zadko images where fake on-axis GRB and kilonova optical transients were injected.

Estimates of the rate of false detections may be deduced from the occurrence of detected optical transients that would be unrelated to the GW event and observed by chance in the field. The contaminant transients that are able to pass the light-curve cut include some rapid variable Cepheid stars and Active Galactic Nuclei.

4 Concluding remarks

The present paper reports on the first EM follow-up program to GW candidates performed by the LIGO/Virgo collaborations together with partner observatories. This follow-up program is a milestone toward the advanced detector era. With a ten-fold improvement of sensitivity ¹⁹, the number of detectable sources increases by a factor of 10³. It is likely that advanced detectors will make the first direct detection of GWs. The observation of an EM counterpart may be a crucial ingredient in deciding the astrophysical nature of the first event.

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